

Creating a Lunar EVA Work Envelope

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ABSTRACT

A work envelope has been defined for weightless Extravehicular Activity (EVA) based on the Space Shuttle Extravehicular Mobility Unit (EMU), but there is no equivalent for planetary operations. The weightless work envelope is essential for planning all EVA tasks because it determines the location of removable parts, making sure they are within reach and visibility of the suited crew member. In addition, using the envelope positions the structural hard points for foot restraints that allow placing both hands on the job and provides a load path for reacting forces.

EVA operations are always constrained by time. Tasks are carefully planned to ensure the crew has enough breathing oxygen, cooling water, and battery power. Planning first involves computers using a virtual work envelope to model tasks, next suited crew members in a simulated environment refine the tasks. For weightless operations, this process is well developed, but planetary EVA is different and no work envelope has been defined.

The primary difference between weightless and planetary work envelopes is gravity. It influences anthropometry, horizontal and vertical mobility, and reaction load paths and introduces effort into doing "overhead" work. Additionally, the use of spacesuits other than the EMU, and their impacts on range of

motion, must be taken into account. This paper presents the analysis leading to a concept for a planetary EVA work envelope with emphasis on lunar operations. There is some urgency in creating this concept because NASA has begun building and testing development hardware for the lunar surface, including rovers, habitats and cargo off-loading equipment. Just as with microgravity operations, a lunar EVA work envelope is needed to guide designers in the formative stages of the program with the objective of avoiding difficult and costly rework.

INTRODUCTION

A former mayor of Boston said, "There go my people. I am their leader. I must catch up." Likewise, for NASA's planned lunar outpost, there go the designers. They're supposed to have requirements. We must catch up. Lunar surface systems are being designed but this work proceeds without an EVA work envelope. This paper presents a concept that allows engineers to begin designing surface systems for efficient assembly, access and servicing. Fig. 1 shows the weightless EVA envelope and section 14.4.2.1 of NASA Standard 3000 states the following envelope design considerations:

- The work envelope, mobility range, and visual field-of-view of the suited crew member should be considered in workstation design.

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- EVA workstations should be designed to accommodate the characteristics of the suited female and the suited male user population.
- The effects of neutral body position on the EVA crew member's line-of-sight should be taken into consideration in workstation design.

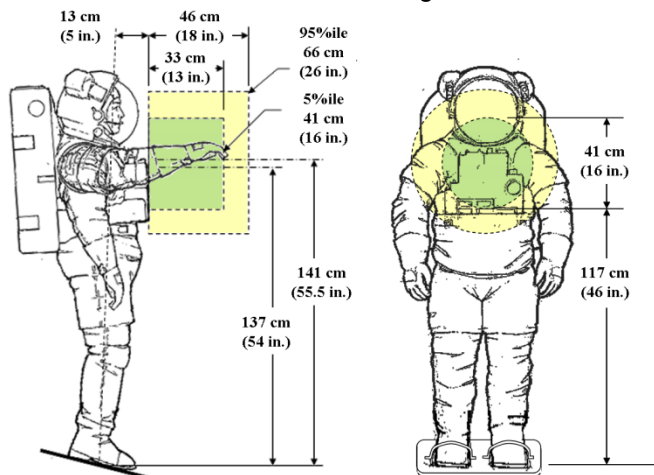


Figure 1 Weightless EVA Work Envelope

The Apollo missions ended in 1972, providing photographs, video and first-person accounts of lunar EVA. No work envelope was produced and since then all EVA has been weightless. In fact, with the planned 2020 lunar landing, over 50 years will separate the first Apollo landing from the next set of lunar boot prints. This is significant, because a gravity-based EVA philosophy will have to overtake a culture of weightless operations. What is now a highly orchestrated infrequent event will become routine, driven by the opportunities of exploration as well as outpost assembly, repair and the operations of In-situ Resource Utilization.

In zero-g, astronauts “walk” with their arms and lock boots into foot restraints to provide a stable work position. On the Moon, astronauts walk upright, which significantly changes the approach to EVA. In weightless operations, the foot restraint brings the astronaut within reach of the task. However, on the Moon, the challenge is bringing the task within reach of an astronaut standing on the surface.

ANTHROPOMETRY

LUNAR GRAVITY – Gravity plays an important role in human physiology and anthropometry. See Fig 2. [2] For example, on the Earth while sitting, standing or walking, our vertebrae are compressed under the force of gravity. However, in zero-g, the vertebrae unload, resulting in as much as 5.1 cm (2 in.) elongation of the spinal column. This elongation is significant for

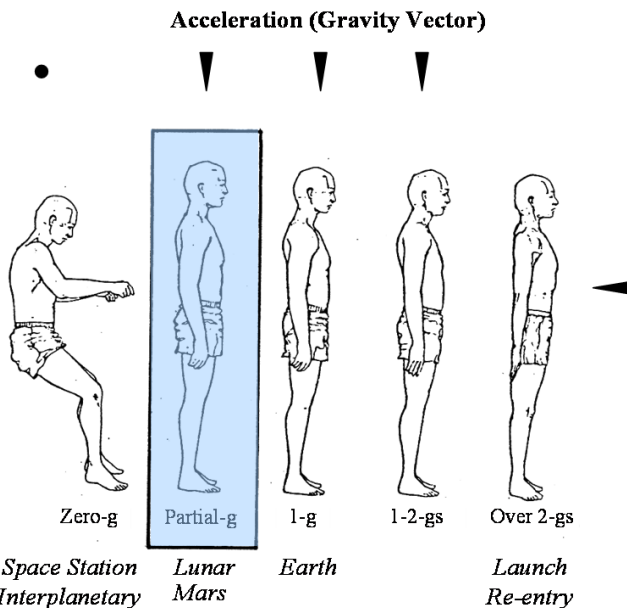
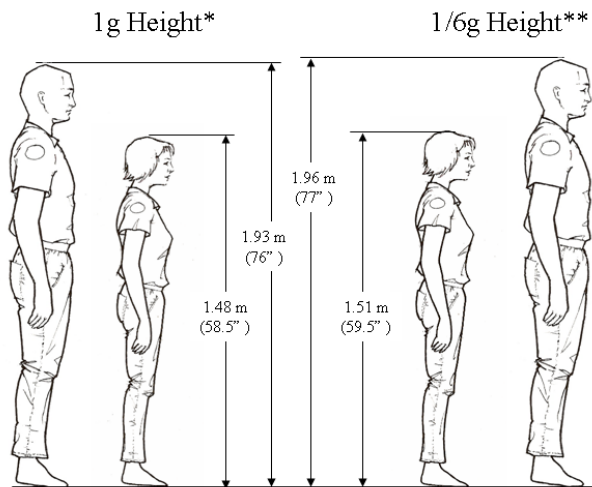


Figure 2 Postures in Response to Acceleration

EVA, because the fit of the pressure suit directly affects the ability to do any task. A proper fit is accomplished by assembling and adjusting parts to match body measurements and then “tuning” these dimensions to accommodate individual preferences. Using this approach, suits are configured for individual crew members and used in neutral buoyancy training of mission tasks. Neutral buoyancy approximates weightless operations but is still under the influence of earth’s gravity, meaning that suits are sized for 1-g. Because the weightless vertebral extension is understood, technicians are able to determine and apply adjustments to the suits before launch. Apollo surface stay times were no more than 3 days and the Lunar Module cabin was too confined to observe any anthropometric changes. However future lunar missions are planned for up to 180 days, allowing enough time for crew members to adapt to lunar gravity. For this analysis, it is assumed the vertebrae will partially un-load resulting in a change in the vertebral column thereby affecting height and head position.

It is difficult to get actual measurements on Earth of the effects of partial gravity. Bed rest studies and underwater compensations do not adequately reflect prolonged exposure to 1/6 g. So, it was assumed that there would be some extension to a partially unloaded vertebral column, although less than in 0-g, resulting in 2.5 cm (1 in.) added to the 1-g stature of all crew. See Fig. 3. Accordingly, a reshaped vertebral column would slightly change head position and field of view, resulting in 5 degrees down from horizontal vs. 10 degrees down in 1-g.



* Pilot and Mission Specialist astronaut range
 ** Assumes unloading of vertebral column due to prolonged exposure to lunar gravity

Figure 3 Lunar Gravity Height Adjustment

Without gravity, not only do vertebrae unload, but astronauts adopt a position known as neutral body posture. In this position, the muscles are essentially in a balanced state. Consequently, this posture is used in designing the null position for weightless space suits. Based on observations of Apollo EVAs and 1/6g tests performed in Russia's Zvezda facility, there is speculation that a lunar neutral suited posture exists.[3] A particular neutral position was not used in this study, but there is no evidence to suggest that it is incompatible with the proposed work envelope.

DESIGN POPULATION

The current anthropometric requirements for pilot and mission specialists were used for this study because it allows for a comparison with the weightless work envelope. As data becomes available, results will be updated to reflect the Constellation Program design population.

PRESSURE SUIT ACCOMMODATIONS

All Go EVA

Not all astronauts that travel to the International Space Station go outside and of the three men on each of the six Apollo missions, only two walked on the Moon. Plans for returning to the Moon include four crew members, all of whom will go to the surface and go EVA. This means that all crew members will be designated as EVA crew so pressure suits will need to accommodate the entire lunar astronaut population. This also means that the lunar EVA work envelope must be designed for all crew members rather than for a specified portion of the astronaut population.

Extremes in Population

The design population is the basis for sizing crew elements within the lunar surface systems. A hatch sized for the largest crew member can accommodate the smallest and a mechanism designed for weakest can be operated by all. On the other hand, the work envelope is defined by the common area accessible by both extremes.

PRESSURE SUIT ASSUMPTIONS

The design of the space suit influences the work envelope and even though it will be some time before a new lunar suit is built, there are methods to approximate the performance. Fig. 4 shows the Apollo suit, the only

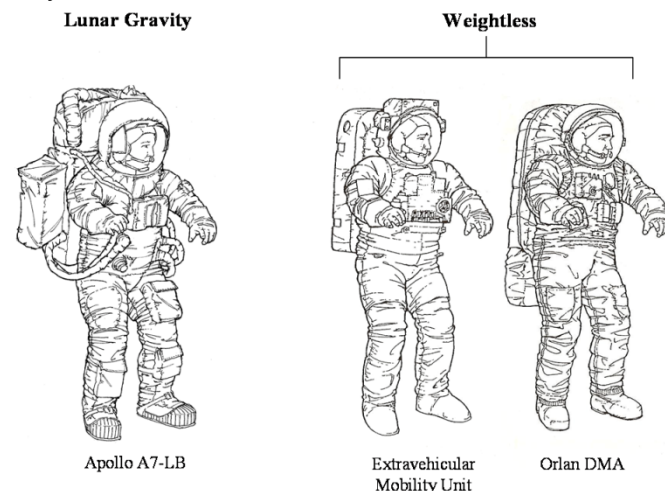


Figure 4 Lunar and Weightless Space Suits

suit that has been used on the Moon, and two versions of suits used for microgravity EVA used on the International Space Station.

A new lunar suit will be designed for walking and will likely have a rear entry feature for donning and doffing. To aid in mobility and dexterity, the suit is assumed to be a low pressure 29.6 kPa (4.3 psi), constant volume, single-gas (oxygen) system. Furthermore, it is assumed that the suit has no chest-mounted equipment. There are many other suit characteristics, but these have the greatest influence on the envelope geometry and dimensions. The Mark III suit shown in Fig. 5 was chosen as a reference design, because it is a rear-entry

walking suit and its performance is well understood.

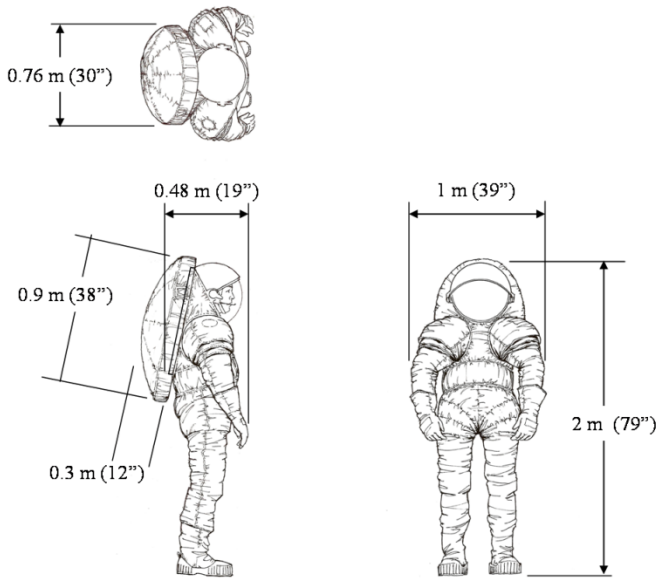


Figure 5 Reference Rear-entry Suit- Mark III

EVA WORK ENVELOPE

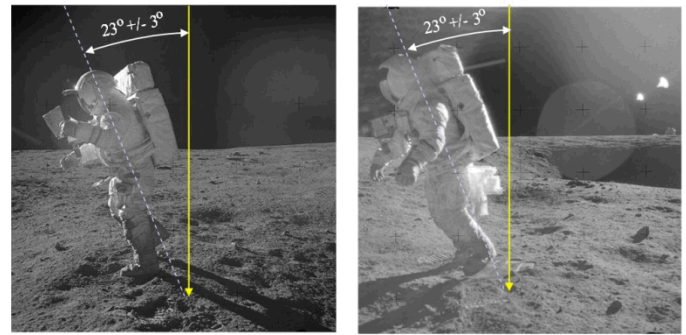
IMPLICATIONS OF SUIT DESIGN

The work envelope for weightless operations relies heavily on suit reach and visibility from a fixed site. On the Moon, crew members can move around the task. This means that different foot locations may offer improved operations and tasks can be planned using multiple locations.

The rear-entry suit configuration implies geometrical relationships that affect reach. First, the opening must be wide enough to accommodate the largest crew member and should be planar to provide a good sealing interface with the backpack. The result is that the shoulder joints are rotated forward ahead of the planar opening. Next, the helmet needs to be in front of the planar opening mounted at a downward angle to provide good visibility. Both joint location and helmet angle work to provide excellent forward reach with good visibility of both gloved hands.

EFFECTS OF GRAVITY

Like carrying a backpack on the Earth, astronauts on the Moon shift their center of gravity (cg) to compensate for the weight of the Portable Life Support System (PLSS). The Apollo PLSS had a mass of 60.8 kg (134 lb) [4]. In Fig. 6, astronauts from two Apollo missions are shown



Edgar Mitchell, Apollo 14

Al Bean Apollo 12

Figure 6 Lean Compensating for PLSS Mass

inclined 23 degrees (+/- 3 degrees) off of local vertical. Walking (or loping) accounts for most of the forward cg, but managing the weight of the PLSS adds to the lean.

Initially, it was thought that leaning forward to compensate for the weight of the PLSS would affect the reach envelope. But, the analysis revealed a static lean between 4 and 5 degrees which did not significantly affect reach.

Parametric analysis was used to estimate the range of angles. The PLSS mass for the enhanced EMU is 69.4 kg (153 lb) for the Shuttle and it is 85 kg (187 lb) for the International Space Station version. This means the range for PLSS mass is between the Apollo 60.8 kg (134 lb) and 85 kg (187 lb). The Apollo pressure garment is 35.4 kg (78 lb), the enhanced EMU 55.3 kg (122 lb) and an assumed crew member is 77.1 kg (170 lb). Thirty cm (12 in) was used as the distance between the crew member cg and the PLSS cg. This means that the shoulder would move between 10.6 cm (4.2 in.) and 14.7 cm (5.8 in.), which translates into static lean angles of 4 and 5 degrees. See Fig. 7.

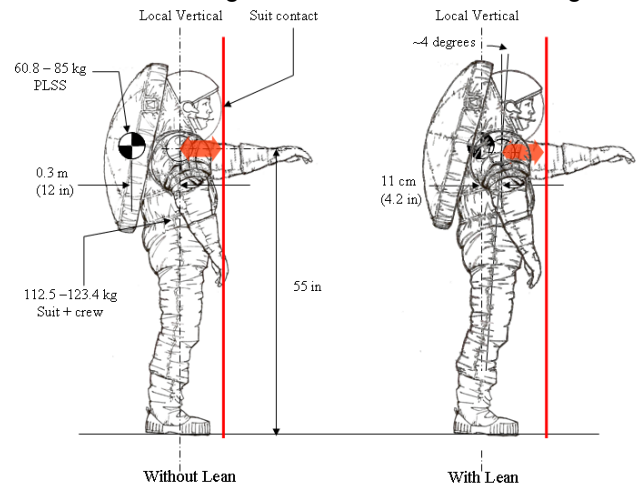


Figure 7 Static Lean and Reach Envelope

More importantly, this does not significantly affect the work envelope, because the critical dimension is between the initial contact point (visor) and the shoulder.

So, regardless of lean angle, when the visor contacts the edge of the work envelope, the reach is established.

DEFINING THE LUNAR EVA WORK ENVELOPE

Reach analysis of suited subjects results in complex shapes that are difficult to apply as a standard for design. Therefore, the challenge for creating an EVA work envelope is to simplify the geometry without compromising the utility.

The objective was to create a large work envelope, but because of the extremes in the design population, this had to be differentiated into prime and secondary envelopes. The prime EVA work envelope (Fig. 8) is the simplified geometry described when both hands are in a fixed field-of-view for the entire design population. The secondary envelope provides extended reach with the upper portion spanning from the shoulder height of the

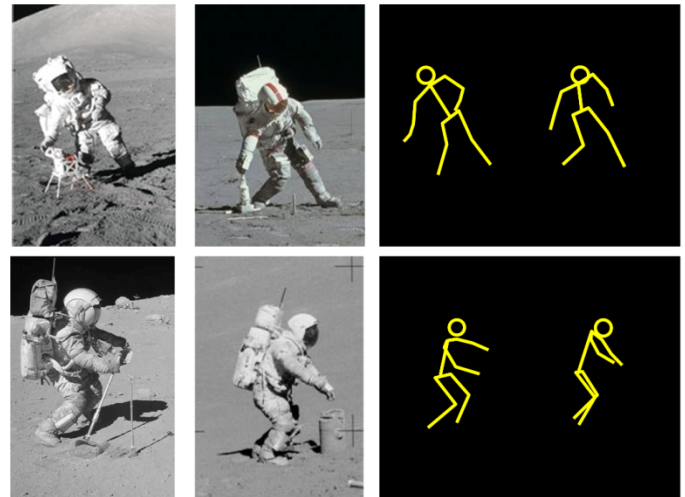


Figure 9 Surface Difficult to Reach in Apollo Suit

The work envelope is slightly different than the reach envelope. At maximum reach, little work can be done with the hands, so the work envelope measures to the grasp area of the glove. Also, because it is assumed that there is no chest mounted equipment, the inner limit of the envelope is at the helmet contact point. Fig 10 shows the work envelope incorporating the static lean for the backpack weight. The key features are vision cutout, primary and secondary envelopes and two-dimensional translation in front of the work area. A vision cutout is incorporated because equipment or vehicle structure may interfere with seeing the prime work area. In its minimum form, the prime work area is represented as

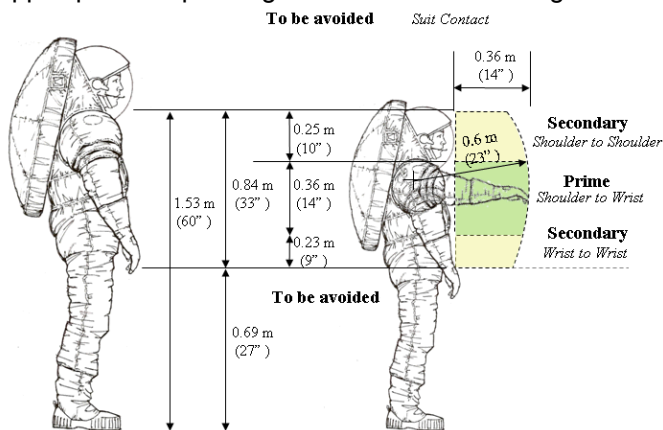


Figure 8 Primary and Secondary Reach Envelopes

tallest crew member to shoulder height of the shortest and the lower portion extends from wrist to wrist of the population extremes.

While some suits are better than others, it is difficult to reach objects on or near the surface. On the Earth, the weight of the upper torso and PLSS helps bending, but as is shown in Fig. 9, in order to reach down, Apollo suit positions used to reach the surface astronauts assumed awkward positions to compensate for suit stiffness and center of gravity. This is why the work envelope is shown for the standing astronaut even though advances in suit design should allow the crew to better reach the surface.

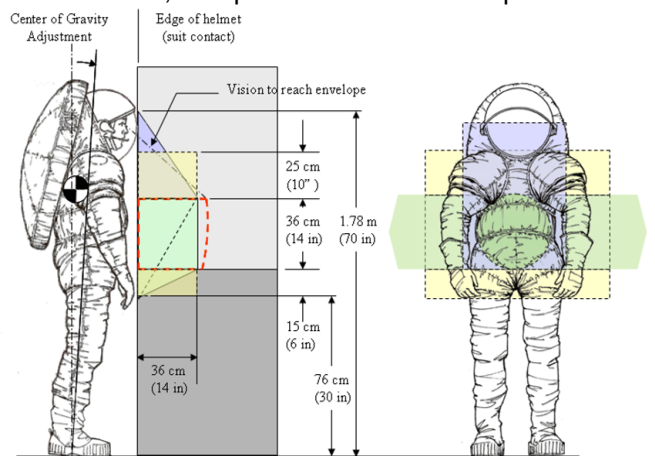


Figure 10 Lunar EVA Work Envelope

a cylinder 36 cm (14 in.) in diameter centered 1.1 m (43 in.) above the surface. Equipment that requires visibility and both gloves on the job should be located within this zone. Two secondary work areas are above and below the prime work area. Equipment or controls that require one hand operation can be located in this zone and are accessible to the entire design population. Unlike the fixed weightless work envelope, the lunar envelopes should be perceived as horizontal bands above the surface.

Fig. 11 shows a dual and single plane version of the work envelope. The dual plane is shaped to accommodate the prime envelope while the single plane option truncates the geometry offering visibility perpendicular to the work plane.

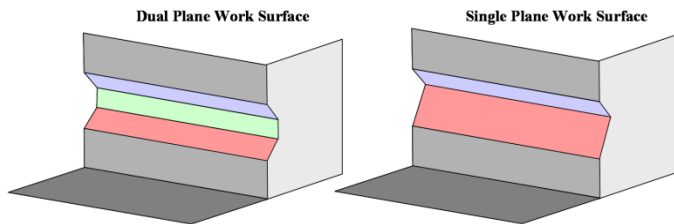


Figure 11 Work Envelope Options

It is possible to assume that the lunar EVA envelope is merely the weightless envelope placed on the surface of the Moon. However, when placed side-by-side there are significant differences. Fig. 12 compares the two envelopes showing a 0.3 m (12 in.) difference in height and, without foot restraints, the lunar envelope is not constrained to a circle, but extends horizontally over the surface.

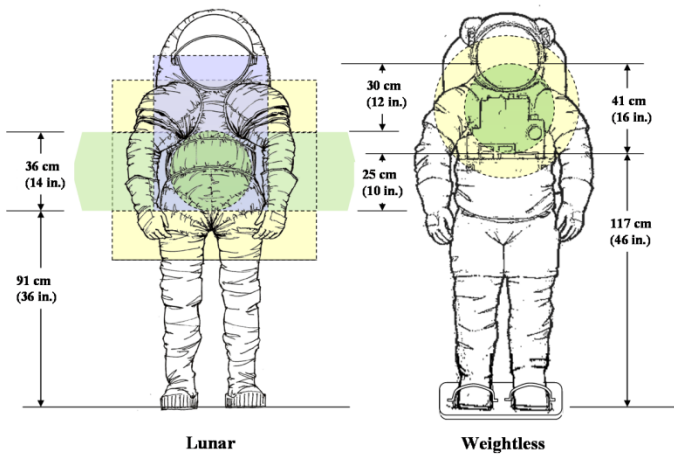


Figure 12 Lunar and Weightless Envelopes

TRANSLATION CORRIDORS

Corridors have been defined for weightless EVA translation and the same thinking applies to the Moon. However, with gravity, the translation is more Earth-like and divided into horizontal and vertical. Horizontal corridors allow the crew to move between objects, while the vertical corridor provides adequate room for moving up and down ladders. The 1 m (39 in) dimension for the horizontal corridor (Fig. 13) is derived from the breadth of the 99th percentile suited crew member without tools. This dimension also works well as the “back wall” for crew members facing the work envelope.

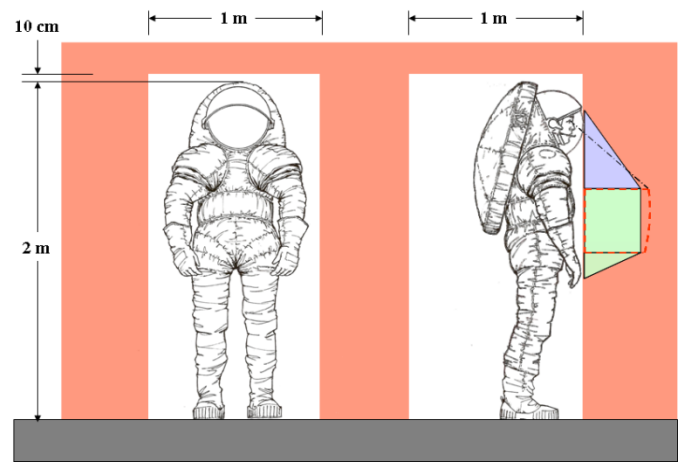


Figure 13 Horizontal Translation Corridor

Climbing ladders in a pressure suit represents a serious safety concern. A fall can damage the suit, leading to death, or there can be injury due to the body hitting the inside of the suit. Suit bulk and joint mobility inhibit the typical climbing motion and grasping the ladder requires repetitive glove operation. While the lunar suit has not been designed, weight is still a concern. For each trip up and down the ladder, astronauts are essentially carrying their suits, backpacks and possibly tools. Adjusted for lunar gravity excluding the weight of the astronaut, an Apollo suit and PLSS weighed approximately 16 kg (35 lb) and the equivalent weight for an ISS EMU is 23.4 kg (51 lb).

Fig. 14 shows a vertical translation corridor sized for the largest suited crew member. There is 0.04 m (1.5 in.) on either side with 0.18 m (7 in.) boot space and 0.12 m (4.75 in.) for climbing motion. Another 0.03 m (1.2 in) is provided from the climbing motion to the back edge of the corridor.

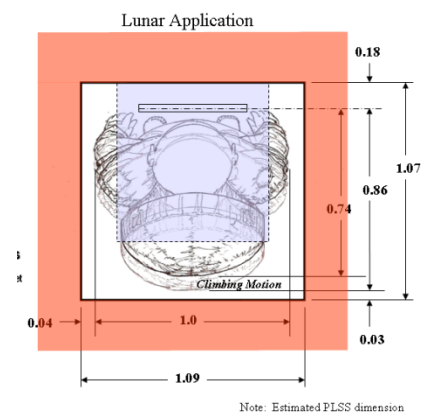


Figure 14 Vertical Translation Corridor

Climbing ladders becomes an issue because current plans call for EVAs from the deck of a lander that is over 6.3 m (21 ft.) off the surface. Without a mechanical lift, each astronaut will climb up and down the ladder for every EVA from the crew lander and will likely climb ladders to assist in off-loading the cargo landers. On the Earth, OSHA requires ladders over 6.1 m (20 ft.) to have a cage, well, or ladder safety device [5].

Another factor affecting the translation corridor is visibility. For horizontal translation, crew visibility is in the direction of translation. In contrast, for vertical translation, the crew member's vision is perpendicular to the direction of movement (see Fig. 15).

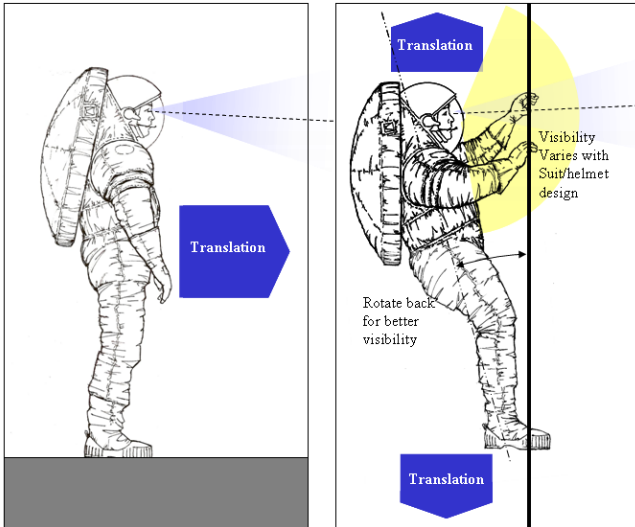


Figure 15 Visibility for Vertical Translation

Ladder climbing is much like weightless EVA and, to provide translation path visibility without changing the body position, the Russian Orlan space suit is equipped with an overhead viewing port. (See Fig. 16) For the Moon, this feature would help climbing a ladder; however, downward visibility is still obscured. Although the crew member may not have downward visibility, markings on the ladder as well as room to lean back or swing out, could provide better sight lines both up and down the ladder.



Figure 16 Visor Opening for Overhead Viewing

CONCLUSION

Plans for returning to the Moon rely heavily on EVA for many tasks including exploration, outpost assembly, lander offloading, ISRU, as well as equipment servicing and repair. The Lunar EVA Work Envelope presented in this paper begins the process of defining the interface between crew and equipment. It is important because EVA is time-sensitive benefiting from the efficient integration of hardware design and astronaut operations. Without the EVA envelope, systems are likely not to be serviceable, take too much time or represent an unnecessary safety risk. To avoid these problems, the Lunar EVA envelope provides guidance to engineers for shaping the designs of lunar surface systems.

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